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Research Paper

Spatially variable pesticide application in vineyards: Part II, field comparison of uniform and map-based variable dose treatments

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Reducing pesticide use is an important concern for many including the European Commission. One way to achieve this goal is to adjust the amount of pesticides in relation to canopy geometry and foliage. This objective currently poses an important challenge in vineyards with uniform vegetation but it is an added difficulty when the canopy shows spatial variability within the field. Is it possible to set a constant volume rate adjusted to this variability? Or is it more convenient to adjusting different volume rates based on a prescription map? Assuming a plant cell density (PCD) vegetation index from multispectral images to be optimal for detecting variations in vigour, two methods to adjust volume rates in spatially variable vineyards were proposed and tested: i) adjustment of a constant volume rate uniformly applied using a conventional sprayer, and ii) adjustment of two volume rates adapted to two vigour classes according to a prescription map. In both methods, PCD was previously correlated to the leaf area index (LAI), then taking the 70th percentile of LAI to determine adjusted volume rates through DOSA3D decision support system (www.dosa3d.cat/en). Leaf deposition with tracer was analysed to compare the proposed methods with the standard volume rate commonly used in the area. Statistical analysis showed no significant differences between treatments. Since pesticide savings can be achieved using the two methods, specifically 25.6% in adjusted uniform and 25.3% in adjusted map-based treatments, adjusted volume rate strategies can be recommended in vineyards with spatial variability.

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Nomenclature table

Abbreviations

PCD	Plant cell density
LAI	Leaf area index
PPP	Plant protection product
DSS	Decision Support System
NDVI	Normalised difference vegetation index
NIR	Near infrared
R	Red
ISO	International Standard Organization
LMM	Linear Mix Model
CV	Coefficient of variation
LR	Leaf recovery
T	Treatment
V	Vigour
H	Height
D	Depth
HV	High vigour
LV	Low vigour

Symbol

T1, T2, T3	Treatments under study
V	Volume rate (l ha^{-1})
LAI_e	Estimated leaf area index
E	Efficiency
α	Fixed 'volume rate strategy' effect
β	Fixed 'vine vigour' effect
C	Random nested 'vine' effect
D	Positional nested factor 'vine depth'
E	Positional nested factor 'vine height'
T	Treatment

1. Introduction

Since the enactment of European Directive 2009/128/EC on the sustainable use of pesticides (Anon, 2009), various integrated pest management programs have been developed to reduce the amount of plant protection products (PPPs) used in the field. However, pest and disease management in vineyards usually still requires a large number of PPP applications. This is especially relevant for fungicides, with an average of 12–15 annual treatments (Pertot et al., 2017). Downy mildew (*Plasmopara viticola* Berl. & de Toni) is one of the diseases that requires the largest number of treatments, and PPPs that contain copper are commonly used for its control (Cabús et al., 2017). However, the European Commission has recently reduced the maximum amount of copper that can be used to 28 kg ha^{-1} for a 7-year period (average 4 kg ha^{-1} $year^{-1}$) (Anon. Commission Implementing Regulation (EU), 2018/1981).

Due to these official restrictions, PPP dose adjusting techniques are becoming more relevant in viticulture. To achieve dose reductions without affecting protection efficacy, many authors propose adapting the dose to the canopy characteristics (or target surface to be treated). In the case of three-dimensional (3D) crops, this is done by estimating the target surface to be sprayed and calculating the optimum volume rate to be applied that provides the minimum coverage of the target area that ensures product efficacy. This is especially relevant in the case of trellised vineyards since the vegetative cycle begins with non-green vegetation until the full development stages. To facilitate the calculation, several decision support systems (DSS) have been developed for vineyards: Optidose® (Davy et al., 2010), DOSA3D (Planas, Román, Sanz, & Rosell-Polo, 2016), Dosaviña (Gil et al., 2019) and Dosage adapté (Viret, Siegfried, Wohlhauser, & Raisigl, 2005). DOSA3D is the updated version of Dosafrut (Planas et al., 2013), and has been adapted for different 3D crops using the same base calculation principles. DOSA3D (www.dosa3d.cat/en) has been used in this work. To decide the optimum volume rate (and doses) adapted to canopy dimensions and leafiness, vineyard LAI estimation is based on the method established by Sanz et al. (2018).

Vineyards are often spatially variable in vigour. Possibly due to factors linked to soil variability, grapevines usually present different canopy volume and leaf development depending on the location within the plot. This spatial variability has been referred to by many authors working on soil characterisation (Martinez-Casasnovas, Agelet-Fernandez, Arno, & Ramos, 2012) or grape yield and phenology mapping (Arnó, Rosell, Blanco, Ramos, & Martínez-Casasnovas, 2012; Bramley & Hamilton, 2004; Verdugo-Vásquez et al., 2019). It is this use of remote sensing that has allowed within-field variability in vigour to be described and, as appropriate, easily delimited according to potential management zones (Borgogno-Mondino, Lessio, Tarricone, Novello, & de Palma, 2018). Although the normalised difference vegetation index (NDVI) has been widely used in agriculture, the plant cell density (PCD) or ratio vegetation index has generally been used in applications within the scope of precision viticulture. The PCD is similar to the NDVI in that the difference between the high reflectance in the near-infrared waveband versus the low reflectance in the red waveband is highlighted. However, areas of higher vegetation density are better contrasted through PCD images than NDVI images. This difference is probably attributable to the greater ability of PCD to detect differences in the photosynthetically active biomass (Proffitt, Bramley, Lamb, & Winter, 2006).

In short, knowing in advance the foliar variability within a plot is a tool that can be used repeatedly if its impact on improving treatment efficiency is clearly demonstrated. Volume rate adjustment according to delimited areas of different vigour is a real possibility (Campos et al., 2019, 2020; Román & Planas, 2018). Moreover, some diseases also seem to be correlated to vine vigour. Ferrer et al. (2019) showed a relationship between high vigour areas within a vineyard and fungus attack due to the lack of water restriction in these areas. Bramley, Evans, Dunne, and Gobbett (2011) revealed that high vigour areas tended to be more affected by botrytis

(*Botrytis cinerea* Pers.) compared to areas of lower vigour development, and Román and Planas (2018) also showed the influence of high vigour areas on the abundance of yellow spider mite (*Eotetranychus carpini* Oud.). However, none of the DSS mentioned above take into account the assumption of within-field variability in crop vigour when volume rates are recommended.

Consequently, it might be necessary to adapt PPP dose to vine vigour. This adaptation could be done using real-time technologies to sense crop vigour status. Different real-time variable rate technologies have been shown to be able to adapt dosage to canopy characteristics and qualitatively and quantitatively improve the sprayed deposition (Wandkar, Bhatt, Jain, Nalawade, & Pawar, 2018). Variable rate application usually requires the use of sensors and electronic devices mounted on the sprayer that may require specific technical training for the operators, and they are still economically beyond the reach of small- and medium-sized wine growers (Tona, Calcante, & Oberti, 2018). Major growers are reluctant to implement these devices because of their reliability and maintenance needs, as well as for reasons of cost. Nevertheless, vigour maps that growers use for other vineyard management practises can be adapted for site-specific PPP applications (Campos et al., 2019, 2020), and low cost pressure controllers could be mounted in sprayers to allow variable rate spraying to be adopted by many farmers with savings of around 10–27% in PPP costs (Petrović, Mladen, Tadić, Plaščak, & Barač, 2018).

A two-stage research programme was designed to address the problem of PPP dosing when vineyard plots are spatially variable in vigour. In Part I, a geostatistical approach was developed that included demonstrating how geostatistics could allow optimal volume rates in spatially variable plots to be adopted. Specifically, it was proposed to use LAI values in volume rate expressions between the 65th and 80th percentile as ancillary information to minimise the risk (probability) of vulnerable areas being underdosed. Field validation allowing the proposed method to be assessed under real application conditions constitutes the main objective of this paper (Part II), completing the second phase of the research. In short, the aims of this paper are (i) to validate by on-target spray deposition measurement the methodology proposed in Part I to adjust volume rates for uniform and map-based treatments in vineyards with spatial variability in vigour, and (ii) to establish a protocol that integrates the use of the DOSA3D decision support system to recommend volume rates and doses in spatially variable vineyards.

2. Material and methods

2.1. Vineyard

The experiments were carried out in 2017 and located at Raïmat, Spain (41°41′52.92″N, 0°29′18.56″E). They were conducted in a commercial 17.5 ha vineyard var. Cabernet Sauvignon during the fruit development growth stage (BBCH scale: 71–73) (Meier, 2001). Grapevines were planted in 2011 in a trellis system with 2.50 m spacing between rows and 1.65 m spacing within the rows (Fig. 1).

2.2. Maps

A multispectral airborne image was taken on 25 May 2017 using a 4-band multispectral camera. The 50 cm spatial resolution image was supplied by Agropixel SL (Lleida, Spain). The spectral regions captured were: (i) blue (445–520 nm), (ii) green (510–600 nm), (iii) red (510–600 nm), and (iv) near-infrared (757–853 nm). The high resolution of the image allowed pixels on grapevines to be precisely delimited. The pixels outside the canopy corresponding to the inter-row spaces were then deleted, avoiding distortions in vigour interpretation. The PCD index (Bramley, Pearse, & Chamberlain, 2003) was then calculated for each canopy pixel using:

$$PCD = \frac{NIR}{R} \tag{1}$$

where NIR refers to near-infrared and R to the visible spectral region of red. The resulting image was classified into 5 quantiles according to the distribution of PCD values (Fig. 2A). In this way, 3 vines from each PCD quantile were selected and manually defoliated to measure leaves using a leaf-meter (Delta-T Devices Ltd., Cambridge, UK). Once transformed to LAI measures, each LAI value was related to the PCD mean value of the six nearest pixels to the defoliation point by a simple linear regression ($y = 0.0087x$; $R^2 = 0.89$). The resulting equation allowed PCD values to be converted into LAI values for the vineyard pixels. For that, pixels were converted to vector points using ArcMap 10.5 (Environmental Systems Research Institute, Redlands, CA, USA). Then, a continuous LAI surface map was obtained by ordinary kriging using an exponential model for semi-variogram adjustment. The interpolation grid was set at 1 m (spatial resolution), on which the LAI point values were referred (Fig. 2B). Subsequently, the interpolated LAI map was classified into two LAI classes (high and low) using cluster analysis and an unsupervised algorithm (ISODATA, iterative self-organising data analysis technique) implemented in ArcGIS 10.5 (Fig. 2C). Finally, from this classified map, a prescription map to apply two different volume rates was generated by polygonising the original classes and eliminating those smaller than 0.01 ha (Fig. 2D).

2.3. Spray technology

A two-row face-to-face IRIS sprayer fitted with an HF-540 tangential-flow fan (540 mm diameter) (Ilemo Hardi, S.A.U., Lleida, Spain) was used for all treatments (Fig. 3). For application using the prescription map, the sprayer was modified to change the working pressure as necessary. A three-way ball solenoid valve (M853L14A55, Arag S.R.L, Rubeira, Italy) was added to divert the flow to one of the two installed manual pressure regulators (model number 4755612, Arag S.R.L, Rubeira, Italy) (Fig. 4). The working pressure was changed via a bypass switched by the action of the operator each time the zone border was crossed over in accordance with the map and the Global Navigation Satellite System indications shown on the on-board monitor. The on-board monitor consisted of a tablet with PixelMaps 1.0.3 (Agropixel SL, Lleida, Spain) software installed.

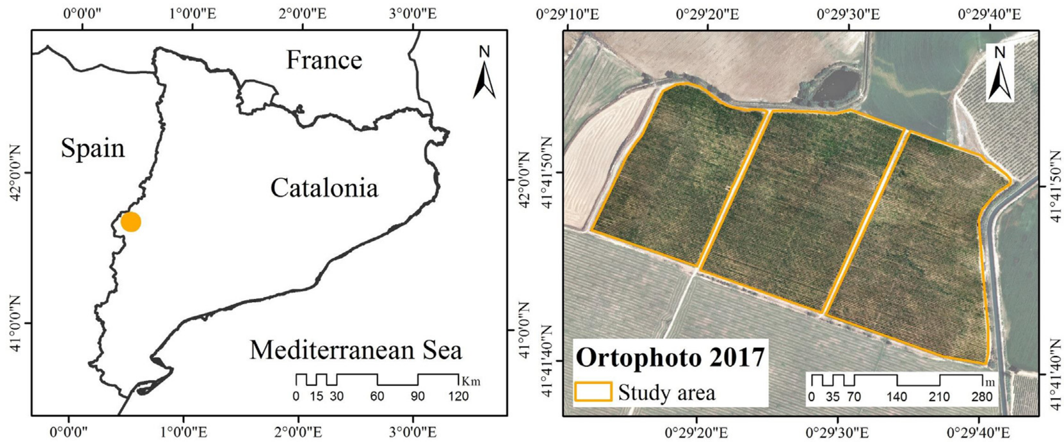

Fig. 1 – Field location and study area.

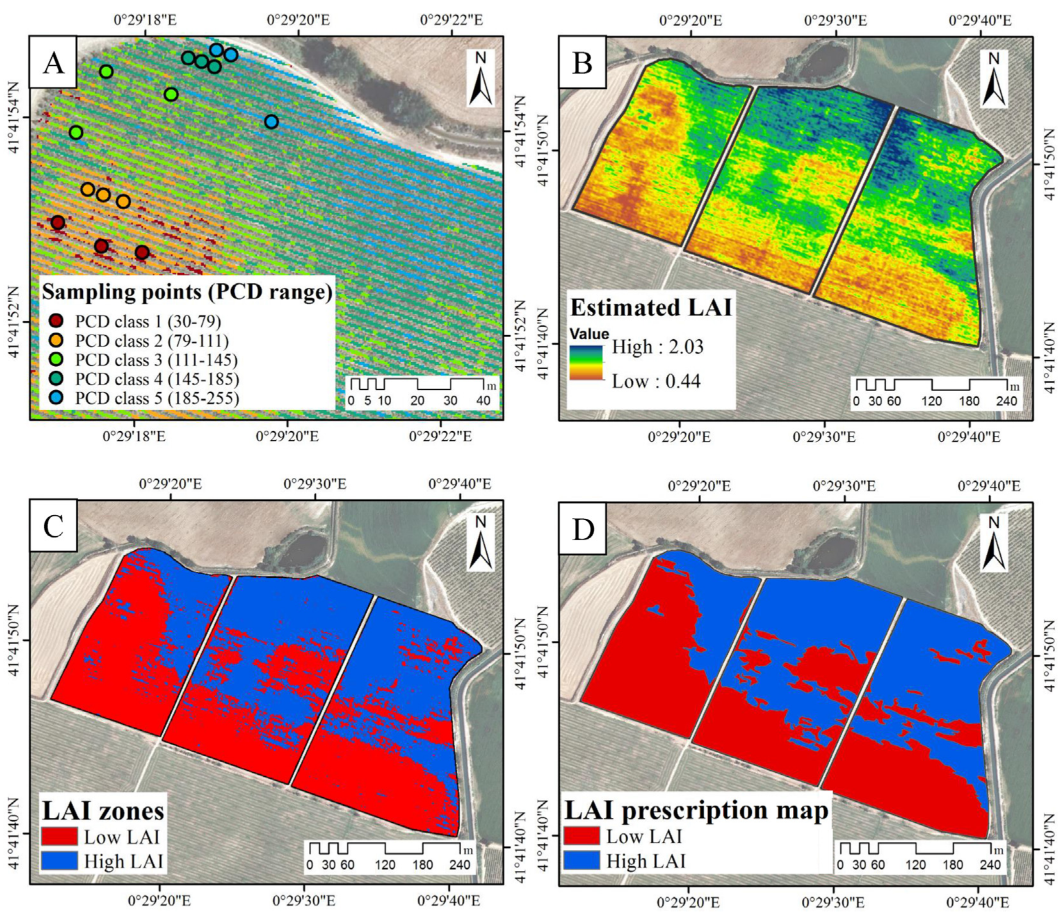

Fig. 2 – A) Sampling points to measure LAI. B) LAI continuous map. C) LAI classification into two vigour classes. D) final prescription map.

Fig. 3 – Two-row IRIS sprayer used in all treatments.

2.4. Experimental design

Three treatment strategies using different volume rates were performed: (i) conventional uniform volume rate set by the farmer (T1, standard volume rate), (ii) adjusted uniform volume rate (T2, adjusted volume rate) and (iii) adjusted map-based volume rates according to two vigour classes (T3, adjusted high and low volume rates). DOSA3D was used to calculate T2 and T3 adjusted volume rates through Eq. (2) below (proposed by Planas et al., 2013).

$$V = \frac{120 * LAI_e}{E} \quad (2)$$

where V is the volume rate in l ha^{-1}, LAI_e is the estimated leaf area index, and E is the treatment efficiency. Considering the

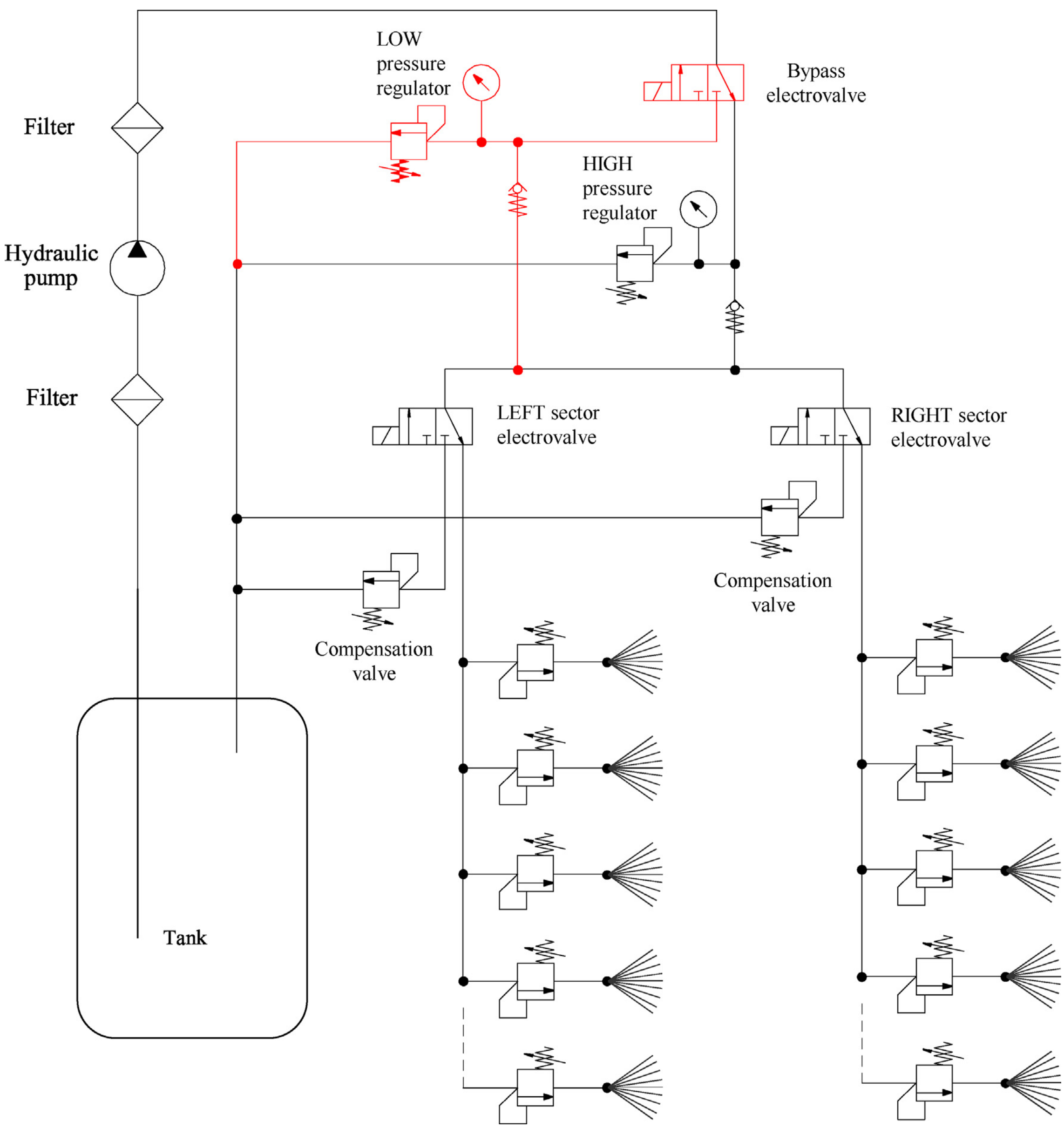

Fig. 4 – Hydraulic circuit of the sprayer. In red: circuit modification for two volume rates application by means of pressure regulators. (For interpretation of the references to Colour in this figure legend, the reader is referred to the Web version of this article.)

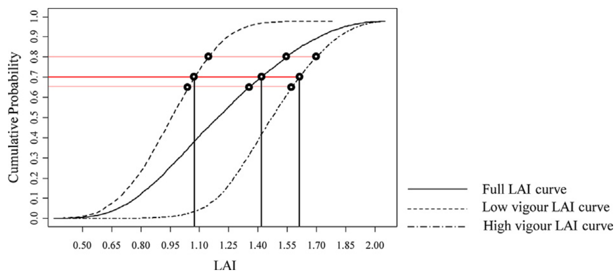

Fig. 5 – Distribution of LAI values and LAI 70th percentile. Continuous curve includes all plot LAI values and correspond to treatment strategy T2 (adjusted uniform treatment) while the dashed and dot-dashed curves represent separately LAI distributions for low and high vigour classes, respectively, and the management of both curves corresponds to treatment strategy T3 (adjusted high and low volume rates).

recommendation of Part I, LAI 70th percentiles (Fig. 5) and a regular efficiency of 50% were used to calculate the adjusted volume rates (Table 1). The tractor power take-off was set at 430 rev min-1. Air speed was measured upon target arrival (canopy) with an anemometer (Meteo Digit type 916, Lambrecht meteo GmbH, Göttingen, Germany) and resulted 5.6 ± 1.1 m s^{-1} (mean ± standard deviation). Forward speed was established by the farmer at 6.5 km h^{-1} and was kept constant for all treatments. The working pressure values were previously established to ensure the volume rate to be sprayed (Table 1). However, to prevent treatments with much lower working pressures than the range recommended by the manufacturer of the nozzles used (1–1.5 MPa), it was decided to increase the application volume rate in the T3 treatment by 14% for low vigour areas.

The experiments were carried out in a small part of the vineyard so that each row contained the two vigour classes (Fig. 6A). Treatments were applied on six continuous rows (0.255 ha), and samples were picked from the two central rows to prevent cross contamination. To analyse depositions, manganese (Sarcan Mn 13%, Exclusivas Sarabia, Lleida, Spain) was used as tracer (Table 1). In accordance with the requirements of ISO 22522:2007 (ISO, 2007), leaf spray depositions were measured in three randomly selected vines per vigour class and treatment. In each vine, nine different positions of the canopy were sampled according to different heights and depths (three heights and three depths within the canopy, Fig. 6B). For each sampling position, 3–5 leaves were collected, introduced in a zip-lock bag and stored in dark conditions until laboratory analysis. Manganese (Mn^{++}) was determined by means of atomic absorption spectrometry (AAnalyst 400, Perkin Elmer, Waltham, USA). Spray Mn^{++} depositions were then related to sample surface area and expressed as µg cm^{-2}. Tracer concentration in the tank and blank samples taken before treatments were also quantified.

Table 1 – Volume rates, sprayer settings and dose rates of manganese by treatments. T1: standard uniform; T2: adjusted uniform; T3: adjusted map-based.

Treatment		LAI_{70} percentile	Volume rate (l ha^{-1})		Nozzle model (number)	Working pressure (MPa)	Mn^{++} (g l^{-1})
			Calculated	*Measured*			
T1		–	450	456	Albuz ATR yellow (24)	1	1.90
T2		1,42	341	340	Albuz ATR yellow (20)	0.8	1.95
T3	Low vigour	1,08	259	295	Albuz ATR yellow (16)	0.7	1.95
	High vigour	1,62	389	387	& Albuz ATR brown (4)	1.2	

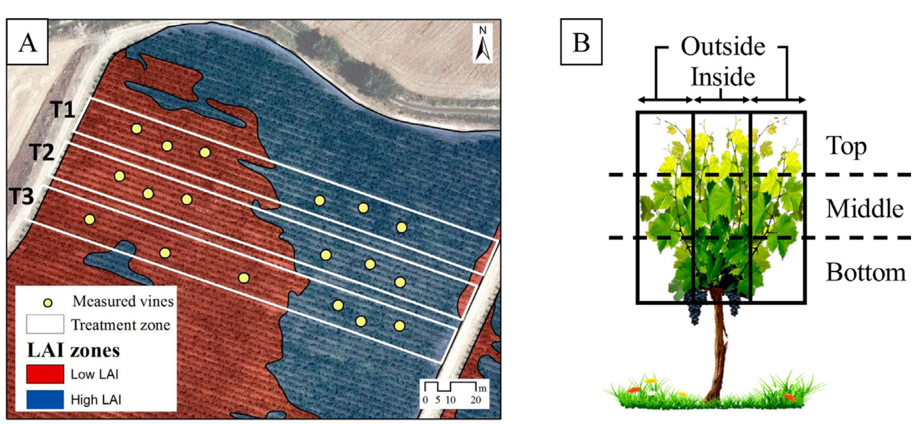

Fig. 6 – Experimental design. A) Treatments location inside the vineyard. Dots indicate sampled vines location. B) Sampled zones within the vines.

2.5. Data analysis

Leaf deposition was statistically analysed using a linear five-factor model with mixed effects (LMM), considering treatment strategy and vine vigour as fixed factors and the sampled vines and deposition zones within the vines (height and depth) as random factors. A total of 9 mean deposition values from each vine were obtained depending on the location (deposition zone) sampled within the canopy, and this for each of the crossed levels of the fixed factors. The final model was (3):

$$y_{ijklmn} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + C_{k(ij)} + D_{l(k(ij))} + E_{m(k(ij))} + DE_{lm(k(ij))} + e_{ijklmn} \quad (3)$$

where $i = 1, \ldots, 3$, $j = 1,2$, $k = 1, \ldots, 3$, $l = 1,2$, $m = 1, \ldots, 3$, $n = 1$ for $l = 1$ and $n = 2$ for $l = 2$, with y_{ijklmn} the deposition value n obtained within the canopy at height m (top, middle or bottom) and depth l (inside or outside of the canopy) for the vine k within the combination of vigour class j (low or high) and volume rate strategy i (treatment T1, T2 or T3), μ the general average, α_i the effect of level i of the fixed factor A (volume rate strategy), β_j the effect of level j of the fixed factor B (vine vigour), $\alpha\beta_{ij}$ the effect of the interaction between fixed factors A and B, $C_{k(ij)}$ the random effect of vine factor nested in each combination of fixed factors, $D_{l(k(ij))}$ and $E_{m(k(ij))}$ the effects of positional factors 'depth' and 'height' nested within the random factor C (vine), $DE_{lm(k(ij))}$ the interaction between the two previous positional factors, and e_{ijklmn} the error term.

Because of the random character of nested factor C (vine) and, consequently, also for the nested canopy factors 'depth' and 'height', significant variation within these factors was assessed by applying different contrasts arranged, for example, for factor C as follows:

$$H_0 : \sigma_C^2 = 0$$

$$H_1 : \sigma_C^2 > 0$$

As it was possible to obtain the variance components, the relative contribution of each significant random factor on the variation of deposition values was then quantified. In addition to leaf deposits, leaf recovery was estimated as the proportion of the sprayed tracer recovered on target, for which LAI 70th percentile values for each vigour class (Fig. 4) were used as a reference for each treatment strategy under study (standard, uniform and map-based volume rates).

Data were normalised by the standard Mn^{++} treatment concentration, and then square root transformation was applied to meet the assumptions of homogeneity of variances (Bartlett test) and normality (Shapiro–Wilk test). Tukey's honest significant difference was used in each case for pairwise multiple comparisons to search for specific differences. Open source R software (RStudio 1.2.1335 using R 3.3.2) was used for data analysis.

Table 2 – Normalised manganese deposit average values, coefficient of variation (CV) and leaf recovery (LR) for each treatment (T1: standard uniform; T2: adjusted uniform; T3: adjusted map-based) and vigour class (HV: high vigour; LV: low vigour).

Treatment	Vigour	Leaf deposition (μg cm^{-2})		
		mean ± SE	CV (%)	LR (%)
T1	HV	2.32 ± 0.32	72.4	43.3
	LV	2.69 ± 0.34	66.3	33.5
T2	HV	1.61 ± 0.20	65.7	40.5
	LV	2.13 ± 0.29	70.4	35.8
T3	HV	2.93 ± 0.33	59.1	65.2
	LV	2.14 ± 0.21	51.6	41.4

3. Results and discussion

3.1. Spray on target

Mean normalised leaf deposition per treatment and vigour class are reported in Table 2. Comparing adjusted treatments (T2 and T3) to standard (T1), T2 achieved the lowest deposition both in high and low vigour classes, while T3 increased normalised deposition in high vigour areas and decreased it in areas of low vigour within the plot. However, according to the LMM (Table 3), there were no significant differences between treatments or between vigour classes or interaction. On the other hand, the coefficient of variation (CV) is used as a spatial uniformity indicator of leaf deposition within the whole canopy. Analysing this parameter (Table 2), both uniform treatments (T1 and T2) behaved similarly, while the map-based treatment (T3) allowed deposition uniformity to be improved.

Concerning the random effects of the model, height and depth were found to be significant, indicating different patterns of spray distribution within the canopy (Fig. 7). According to the LMM analysis, "height" component variability represents 9.8% of the model. This is probably attributable to the setting of the nozzles, since treatments T2 and T3 were performed with the lowest nozzle of each vertical boom shut-off. Furthermore, the "depth" component proved to be the most significant, with 38.4% of model variability attributed to it. Penetrability, expressed as the ratio between the inside and outside deposits were 45%, 46% and 52% for T1, T2 and T3, respectively. In vineyards, many authors have reported difficulties with a lack of spray penetration during applications.

Table 3 – Results of the linear mixed model (LMM) analysis of variance for leaf deposition.

Source of variation	DF	Sum Sq	LMM ANOVA	
			F-value	p-value
Treatment (T)	2	1.22	2.49	0.1249^{ns}
Vigour (V)	1	0.08	0.34	0.5690^{ns}
T x V	2	0.90	1.82	0.2035^{ns}
Vine [T x V] *random*	12	2.95	0.30	0.9811^{ns}
Vine [T x V] [Height] *random*	36	9.54	1.54	0.0985*
Vine [T x V] [Depth] *random*	18	12.85	4.16	0.0001***
Vine [T x V] [H x D] *random*	36	6.18	1.17	0.2989^{ns}
Residuals	52	7.79	–	–

DF: degrees of freedom; Sum Sq: sum of squares; ns: not significant; *: significant at $p = 0.1$; **: significant at $p = 0.05$; ***: significant at $p \leq 0.001$.

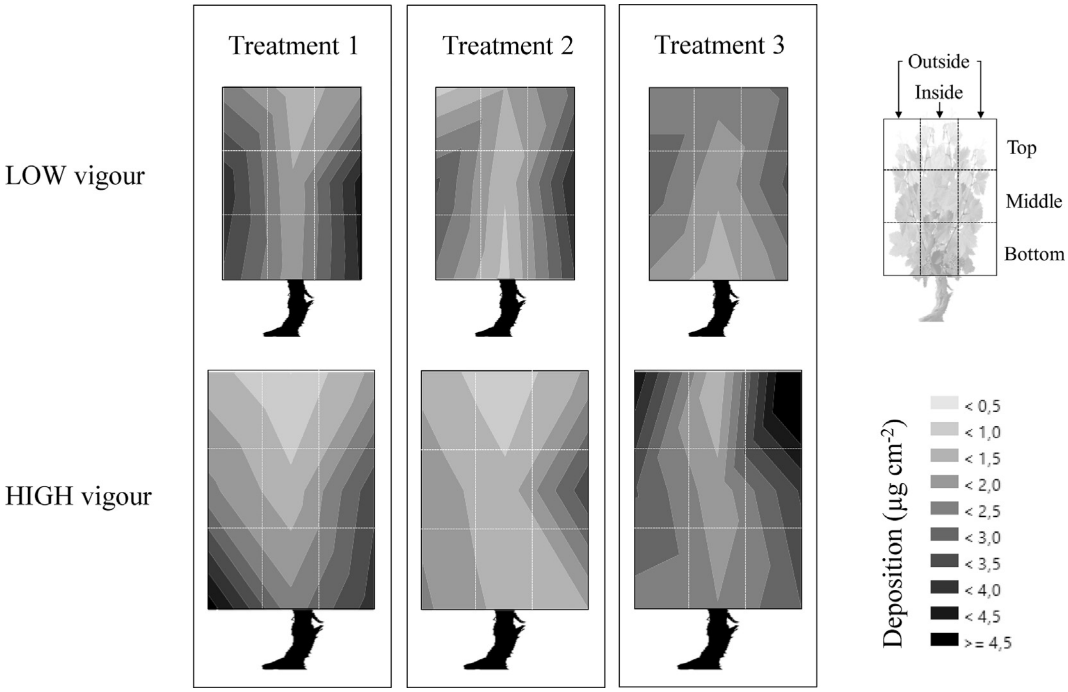

Fig. 7 – Contour plots of mean depositions inside the vines (µg cm^{-2}) by vigour class (low and high) for each treatment (T1: standard uniform; T2: adjusted uniform; T3: adjusted map-based).

However, they agree that spray penetration is maintained or even improved in optimised treatments with adjustment of volume rates compared to conventional treatments (Gil, Escolà, Rosell, Planas, & Val, 2007; Llorens, Gil, Llop, & Escolà, 2010; Pergher, Gubiani, Cividino, Dell'Antonia, & Lagazio, 2013; Román & Planas, 2018). Sprayer operation also plays a key role as optimal calibration can improve leaf deposition by up to 50% (Siegfried, Viret, Huber, & Wohlhauser, 2007).

When comparing leaf recovery as a percentage of the total spray (Table 2), the results coincide with those reported by other authors in that optimised uniform treatments allow similar efficiencies to conventional ones to be obtained, while in variable rate treatments (in this case, based on vigour maps) PPP application efficiency is improved (Gil et al., 2007; Llorens et al., 2010). Moreover, increased recovery in map-based treatment (T3) may indicate a reduction in drift losses (Balsari & Scienza, 2003).

According to Planas et al. (2013), a deposition of 1.2 µl cm^{-2} leaf surface is needed to obtain an optimal leaf coverage and ensure the efficacy of PPP treatments. Leaf Mn^{++} depositions were transformed to µl cm^{-2} and the percentages of samples over this threshold are shown in Fig. 8. Treatment T2 (adjusted uniform) obtained more than 50% of samples with leaf deposits below the threshold proposed by these authors. This may have negative implications in pest and disease control, especially in high vigour areas where only 21% of samples met the proposed premise, with these areas more vulnerable to and at greater risk of phytosanitary problems (Bramley et al., 2011; Ferrer et al., 2019; Román & Planas, 2018). On the other hand, it is assumed that the map-based variable rate treatment (T3) will have a similar biological efficacy to that obtained by conventional treatments (T1).

In the Part I paper, a LAI between the 65th and 80th percentile to calculate optimised volume rates was proposed. According to the results of the present study, in which the LAI 70th percentile was used, it would probably have been more appropriate to use the LAI 80th percentile (1.53) in the case of the adjusted uniform treatment (T2). In this way, the volume rate in treatment T2 would have increased up to 372 l ha^{-1}, similar to that applied in treatment T3 for high vigour areas. Therefore, one would expect similar behaviour in treatment T2 compared to treatments T1 and T3, at least in high vigour

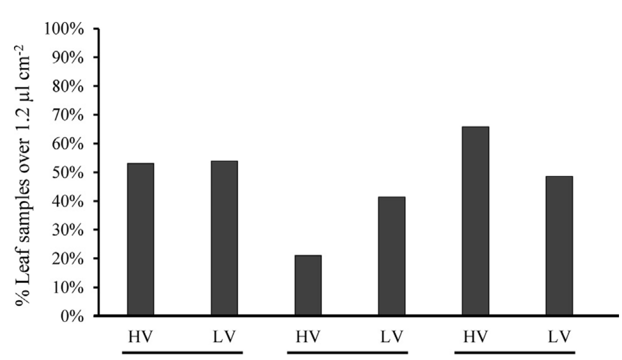

Fig. 8 – Percentage of leaf samples with depositions over 1.2 µl cm^{-2} by treatments (T1: Standard uniform; T2: adjusted uniform; T3: adjusted map-based) and vigour classes (HV: high vigour; LV: low vigour).

areas where grapevines are more vulnerable to disease pressure (Ferrer et al., 2019).

3.2. Savings in pesticide used

In terms of total pesticide savings (Table 4), and assuming the concentration in the tank remains constant, both adjusted treatment strategies achieved similar dose reduction, 25.6% for the adjusted uniform treatment (T2) and 25.3% for the adjusted map-based treatment (T3). The reduction of applied volume keeping the leaf depositions similar in the adjusted treatments (T2 and T3) implies a decrease in the losses compared to the standard treatment (T1) bringing not only economic but also environmental savings. Similar theoretical results were obtained in Part I. Moreover, in the case of adjusted uniform treatments, this result is similar to those obtained by Zhou, He, and Landers (2012) who compared three different volume rate DSSs, obtaining average volume rate reductions of 31% throughout the season. Other studies have reported savings of up to 40% in adjusted uniform treatments (Gil, Llorens, Landers, Llop, & Giralt, 2011). In the case of adopting a site-specific precision crop protection strategy based on real-time sensors, for example using ultrasonic sensors mounted on the sprayer, savings can reach 40–76% (Gil et al., 2007; Llorens et al., 2010). However, the method proposed in this work also achieves satisfactory results taking into account that the objective is to improve the volume rate adjustment for conventional sprayers (predominant among the winegrowers in the area), or to promote the use of slightly modified sprayers that manage to modify the volume rate in only two different values according to a prescription map adapted to areas of low and high grapevine vigour. Another recent study proposes the use of three-class vigour maps using a sprayer prototype allowing treatments based on a prescription map combined with on-the-go on-off volume rate adjustment within each class to be performed. Dose reduction of between 44.3 and 47.3% has been achieved (Campos et al., 2019), basically due to the fusion of map-based and sensor-based technologies and a more accurate performance of the on-board technology. However, according to Tona et al. (2018), the use of these new technologies makes sprayers more expensive and is not economically viable in 10–100 ha farms. Faced with this problem, the proposed method is an option to consider because it is adaptable to the use of conventional sprayers and only requires low-cost technology to be implemented.

Table 4 – Savings comparison between treatment strategies.

		Total area (ha)	Volume rate ($l\ ha^{-1}$)	Total volume applied (l)
(T1) Standard volume rate		17,5	456	7986
(T2) Optimised volume rate		17,5	340	5945
(T3) Optimised class-based volume rates	Low vigour	9,2	295	2718
	High vigour	8,4	387	3250
Savings				
• T2 versus T1				25.6%
• T3 Versus T1				25.3%

4. Practical approaches to decide application volume rates in spatially variable vineyards using vigour maps as ancillary information

While winegrowers with sprayers capable of performing site-specific treatments in vineyards are still very few, the use of multispectral images allowing different vegetation indices (PCD, NDVI) to be obtained is a widespread and accepted practise. So, to add value to DOSA3D as an improved DSS with greater benefits, two practical approaches to decide volume rates in spatially variable vineyards are proposed (Fig. 9). On the one hand, farmers can adjust a uniform volume rate adapted to vineyards variable in vigour (useful for many farms with conventional sprayers) and, on the other, farmers can adjust two volume rates adapted to two different vigour classes previously delimited within the plot (here the use of a specific sprayer is required).

Steps to follow in the adjusted uniform treatment:

1. Take a multispectral image of the vineyard to calculate the PCD index (Fig. 9A).
2. Obtain the PCD histogram to calculate the 80th percentile of the vegetation index distribution. Next, highlight the pixels with this value (or near) on the PCD map to locate the areas that the grower can inspect (Fig. 9C).
3. Select a representative vine within this area (80th percentile) and make a field estimation of the vine canopy dimensions (width and height) (Fig .9D).
4. Use the DOSA3D DSS to obtain a recommended volume rate to apply an adjusted uniform treatment for the entire plot (Fig. 9E).

Steps to follow in the map-based adjusted treatment.

1. Take a multispectral image of the vineyard to calculate the PCD index (Fig. 9A).
2. Classify the PCD image into two vigour classes (high and low) using cluster analysis and an unsupervised algorithm (ISODATA or similar) (Fig. 9B).
3. Obtain the PCD histogram for both vigour classes (high and low) to calculate the 70th percentile of the PCD for each class. Next, highlight the pixels with these values (or near) on the PCD map to locate areas (high and low vigour) that the grower can inspect (Fig. 9C).
4. Select a representative vine within each area (70th percentile of high and low vigour) and make a field estimation of the vine canopy dimensions (width and height) (Fig. 9D).
5. Use the DOSA3D DSS to obtain two recommended volume rates (for high and low vigour areas) (Fig. 9E) to apply an adjusted map-based treatment according to the prescription map.

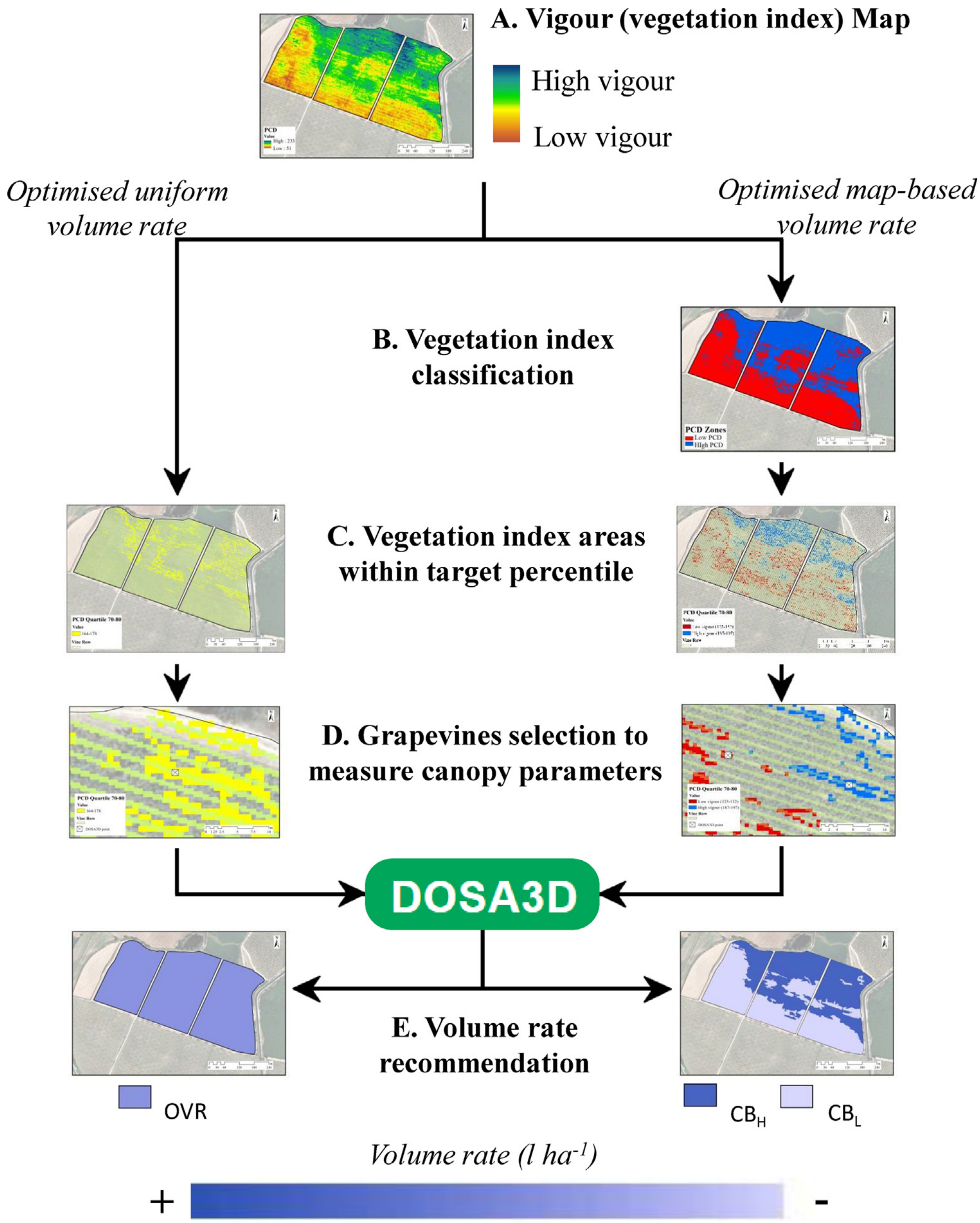

Fig. 9 – Flowchart for obtaining adjusted volume rates from a vigour (vegetation index) map as ancillary information using the DOSA3D decision support system. OVR: Optimised volume rate. CB$_H$: Optimised class-based high volume rate. CB$_L$: Optimised class-based low volume rate.

5. Conclusions

Vineyards are usually variable in their vigour, and this within-field spatial variability in the vine canopy makes it difficult for farmers to decide an optimal application volume rate adapted to this variation when pesticide applications are needed. On the basis of the standard volume rate normally used by many growers, two simplified volume rate adjustment strategies are proposed in this work and validated in terms of efficiency. In both cases, uniform adjusted or map-based, volume rates can be established using a specific percentile of the PCD vegetation index for the field and its corresponding LAI as a reference value to be considered in the DOSA3D decision support system. Our recommendation is to set the 70th percentile of the distribution of the LAI as a threshold value, although the 80th percentile may be more appropriate for uniform treatments at a constant volume rate for the entire plot. Concerning efficiency, pesticide savings of around 25% are expected without observing significant reductions in leaf deposition. This is important for control purposes, although biological efficacy validation remains the pending task. For conventional sprayers, the use of uniform adjusted volumes is an option to consider but better results can be expected in map-based strategies using slightly modified sprayers. In fact, improved uniformity of leaf deposition within the canopy is expected in the latter case since volume rates are better adapted to variable vigour within the plot. Finally, as the proposed protocol is based on the use of the DSS system DOSA3D, this has allowed its scope to be expanded to spatially variable vineyards.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

Anon. Commission Implementing Regulation (EU). (2018). (2018/1981 of 13 December 2018) Renewing the approval of the active substances copper compounds, as candidates for substitution. In *, Vol. 317. Accordance with Regulation (EC) No 1107/2009 of the European Parliament and of the Council concerning the placing of plant protection products on the market, and amending the Annex to Commission Implementing Regulation (EU) No 540/2011. OJ L*, 16–20.

Anon. (2009). Directive 2009/128/EC of the European Parliament establishing a framework for community action to achieve sustainable use of pesticides. *Official Journal of the European Union, L309*, 71–86.

Arnó, J., Rosell, J. R., Blanco, R., Ramos, M. C., & Martínez-Casasnovas, J. A. (2012). Spatial variability in grape yield and quality influenced by soil and crop nutrition characteristics. *Precision Agriculture, 13*(3), 393–410. https://doi.org/10.1007/s11119-011-9254-1.

Balsari, P., & Scienza, A. (2003). *Training systems of the vine and methods for pesticide application*. Milano: Bayer CropScience (in Italian).

Borgogno-Mondino, E., Lessio, A., Tarricone, L., Novello, V., & de Palma, L. (2018). A comparison between multispectral aerial and satellite imagery in precision viticulture. *Precision Agriculture, 19*(2), 195–217. https://doi.org/10.1007/s11119-017-9510-0.

Bramley, R., Pearse, B., & Chamberlain, P. (2003). Being profitable precisely -a case study of precision viticulture from Margaret River. *The Australian & New Zealand Grapegrower & Winemaker Annual Technical Issue*, 84–87. Retrieved from http://www.nwvineyards.net/docs/PVProfitabiltyPaper.pdf.

Bramley, R. G. V., Evans, K. J., Dunne, K. J., & Gobbett, D. L. (2011). Spatial variation in response to "reduced input" spray programs for powdery mildew and botrytis identified through whole-of-block experimentation. *Australian Journal of Grape and Wine Research, 17*(3), 341–350. https://doi.org/10.1111/j.1755-0238.2011.00153.x.

Bramley, R. G. V., & Hamilton, R. P. (2004). Understanding variability in winegrape production systems 2. Within vineyard variation in quality over several vintages. *Australian Journal of Grape and Wine Research, 10*(1), 32–45. https://doi.org/10.1111/j.1755-0238.2004.tb00006.x.

Cabús, A., Pellini, M., Zanzotti, R., Devigili, L., Maines, R., et al. (2017). Efficacy of reduced copper dosages against Plasmopara viticola in organic agriculture. *Crop Protection, 96*, 103–108. https://doi.org/10.1016/j.cropro.2017.02.002.

Campos, J., Gallart, M., Llop, J., Ortega, P., Salcedo, R., & Gil, E. (2020). On-farm evaluation of prescription map-based variable rate application of pesticides in vineyards. *Agronomy, 10*(1), 102. https://doi.org/10.3390/agronomy10010102.

Campos, J., Llop, J., Gallart, M., García-Ruiz, F., Gras, A., Salcedo, R., & Gil, E. (2019). Development of canopy vigour maps using UAV for site-specific management during vineyard spraying process. *Precision Agriculture, 20*(6), 1136–1156. https://doi.org/10.1007/s11119-019-09643-z.

Davy, A., Claverie, M., Codis, S., Bernard, F. M., Colombier, L., et al. (2010). Trials results of the «Optidose» method using an adjustment of the pesticide dose for control of downy and powdery mildew. *Proceedings of the 6th International Workshop on Grapevine Downy and Powdery Mildew. Bordeaux*, 4–9.

Ferrer, M., Echeverría, G., Pereyra, G., Gonzalez-Neves, G., Pan, D., & Mirás-Avalos, J. M. (2019). Mapping vineyard vigor using airborne remote sensing: Relations with yield, berry composition and sanitary status under humid climate conditions. *Precision Agriculture*, 1–20. https://doi.org/10.1007/s11119-019-09663-9.

Gil, E., Campos, J., Ortega, P., Llop, J., Gras, A., Armengol, E., et al. (2019). DOSAVIÑA: Tool to calculate the optimal volume rate and pesticide amount in vineyard spray applications based on a modified leaf wall area method. *Computers and Electronics in Agriculture, 160*, 117–130. https://doi.org/10.1016/j.compag.2019.03.018.

Gil, E., Escolà, A., Rosell, J. R., Planas, S., & Val, L. (2007). Variable rate application of plant protection products in vineyard using ultrasonic sensors. *Crop Protection, 26*(8), 1287–1297. https://doi.org/10.1016/j.cropro.2006.11.003.

Gil, E., Llorens, J., Landers, A., Llop, J., & Giralt, L. (2011). Field validation of dosaviña, a decision support system to determine the optimal volume rate for pesticide application in vineyards. *European Journal of Agronomy, 35*(1), 33–46. https://doi.org/10.1016/j.eja.2011.03.005.

ISO. (2007). *CD 22522: Crop protection equipment - field measurement of spray distribution in tree and bush crops*. ISO Standard ISO TC 23/SC 06.

Llorens, J., Gil, E., Llop, J., & Escolà, A. (2010). Variable rate dosing in precision viticulture: Use of electronic devices to improve application efficiency. *Crop Protection, 29*(3), 239–248. https://doi.org/10.1016/j.cropro.2009.12.022.

Martinez-Casasnovas, J. A., Agelet-Fernandez, J., Arno, J., & Ramos, M. C. (2012). Analysis of vineyard differential management zones and relation to vine development, grape maturity and quality. *Spanish Journal of Agricultural Research, 10*(2), 326–337. https://doi.org/10.5424/sjar/2012102-370-11.

Meier, U. (2001). *Growth stages of mono-and dicotyledonous plants BBCH monograph. Federal biological research centre for agriculture and forestry* (2nd ed.). https://doi.org/10.5073/bbch0515.

Pergher, G., Gubiani, R., Cividino, S. R. S., Dell'Antonia, D., & Lagazio, C. (2013). Assessment of spray deposition and recycling rate in the vineyard from a new type of air-assisted tunnel sprayer. *Crop Protection, 45*, 6–14.

Pertot, I., Caffi, T., Rossi, V., Mugnai, L., Hoffmann, C., et al. (2017). A critical review of plant protection tools for reducing pesticide use on grapevine and new perspectives for the implementation of IPM in viticulture. *Crop Protection, 97*, 70–84. https://doi.org/10.1016/j.cropro.2016.11.025.

Petrović, D., Mladen, J., Tadić, V., Plaščak, I., & Barač, Ž. (2018). Different sensor systems for the application of variable rate technology in permanent crops. *Tehnički Glasnik, 12*(3), 188–195. https://doi.org/10.31803/tg-20180213125928.

Planas, S., Camp, F., Escolà, A., Solanelles, F., Sanz, R., & Rosell-Polo, J. R. (2013). Advances in pesticide dose adjustment in tree crops. In *9th European conference on precision agriculture* (pp. 533–539). https://doi.org/10.320/978-90-8686-778-3.

Planas, S., Román, C., Sanz, R., & Rosell-Polo, J. R. (2016). DOSA3D system. In *EPPO Workshop on harmonized dose expression for the zonal evaluation of plant protection products in high growing crops*. Retrieved from https://www.eppo.int/media/uploaded_images/MEETINGS/Conferences_2016/dose_expression/11_Planas.pdf.

Proffitt, T., Bramley, R., Lamb, D., & Winter, E. (2006). Precision viticulture: A new Era in vineyard Management and *wine (winetitles). Ashford, SA*.

Román, C., & Planas, S. (2018). Adjusted dose treatments through PCD vigour maps in vineyards. *Aspects of Applied Biology. International Advances in Pesticide Applications, 137*(265–1491), 385–392.

Sanz, R., Llorens, J., Escolà, A., Arnó, J., Planas, S., et al. (2018). LIDAR and non-LIDAR-based canopy parameters to estimate the leaf area in fruit trees and vineyard. *Agricultural and Forest Meteorology*, 260–261. https://doi.org/10.1016/j.agrformet.2018.06.017.

Siegfried, W., Viret, O., Huber, B., & Wohlhauser, R. (2007). Dosage of plant protection products adapted to leaf area index in viticulture. *Crop Protection, 26*(2), 73–82. https://doi.org/10.1016/j.cropro.2006.04.002.

Tona, E., Calcante, A., & Oberti, R. (2018). The profitability of precision spraying on specialty crops: A technical–economic analysis of protection equipment at increasing technological levels. *Precision Agriculture, 19*(4), 606–629. https://doi.org/10.1007/s11119-017-9543-4.

Verdugo-Vásquez, N., Acevedo-Opazo, C., Valdés-Gómez, H., Ingram, B., García de Cortázar-Atauri, I., & Tisseyre, B. (2019). Towards an empirical model to estimate the spatial variability of grapevine phenology at the within field scale. *Precision Agriculture, 21*, 107–130. https://doi.org/10.1007/s11119-019-09657-7 (April).

Viret, O., Siegfried, W., Wohlhauser, R., & Raisigl, U. (2005). Dosage des fongicides en fonction du volume foliaire de la vigne. *Revue suisse de viticulture, arboriculture et horticulture, 37*(1), 59–62.

Wandkar, S. V., Bhatt, Y. C., Jain, H. K., Nalawade, S. M., & Pawar, S. G. (2018). June 1). Real-time variable rate spraying in orchards and vineyards: A review. *Journal - The Institution of Engineers, 99*(2), 285–390. https://doi.org/10.1007/s40030-018-0289-4. Series A. Springer India.

Zhou, J., He, X., & Landers, A. J. (2012). Dosage adjustment for pesticide application in vineyards. *Transactions of the ASABE, 55*(6), 2043–2049. https://doi.org/10.13031/2013.42490.